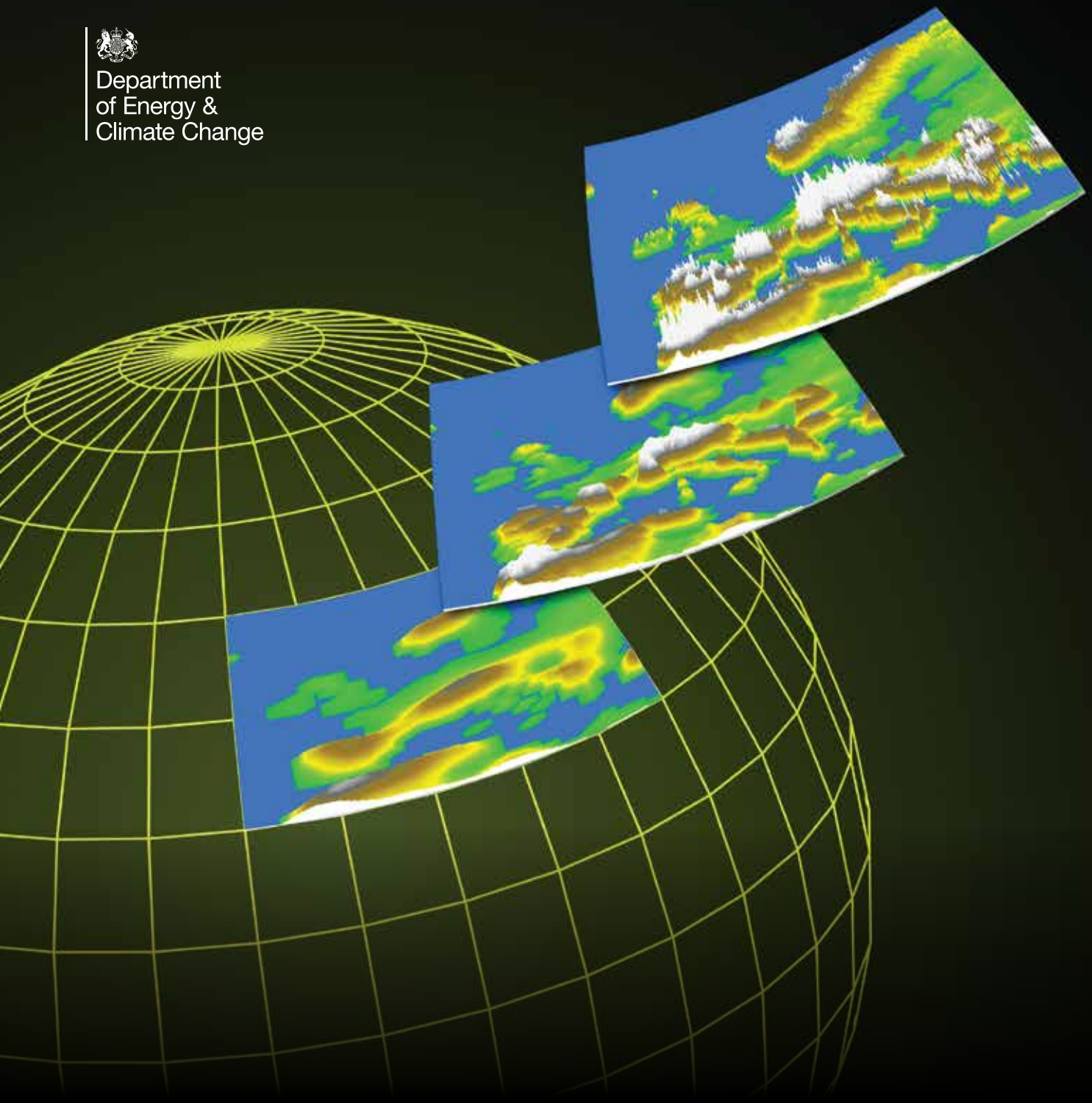
Met Office
Hadley Centre

Department
of Energy &
Climate Change



A summary of the latest science from the Met Office Hadley Centre 2013

The last year has seen developments in climate science associated with improvements in modelling; our understanding of the effects of aerosols on hydrological processes, weather patterns and events; and the carbon budgets necessary to keep within climate warming thresholds.

Key findings described in this brochure include:

- Long-term warming and natural variations combine in the real world. Model statistics suggest slowdowns in warming of around 15 years duration, such as that recently observed, can be expected in a warming climate.

- Consideration of the Earth system's energy storage is helping to explain the recent slowdown in surface warming. There is increasing evidence that some of the additional energy trapped by greenhouse gases is being stored in the deeper ocean, temporarily slowing surface warming.

- Attribution studies of 12 recent extreme events worldwide showed that in half of them there was evidence that human drivers were a contributing factor. For instance, the heatwave of summer 2012 in the USA was a very rare event, estimated to have become four times more likely due to man-made climate change.

- It is not sufficient to consider only greenhouse gases in studies of weather and climate. Man-made pollutant aerosols appear to have been a primary factor in reducing the frequency of 20th century North Atlantic tropical storms and in moderating the Earth's water cycle by suppressing precipitation in opposition to increases from greenhouse gases. There is also evidence that aerosols make Sahelian summers drier.

- A number of future emission pathways have been constructed that give a sizeable probability of limiting warming to 2 °C above pre-industrial levels — a limit adopted by the United Nations Framework Convention on Climate Change (UNFCCC). New research, using a state of the art Earth system model, is investigating the importance of biofuels combined with carbon capture and storage in achieving this long-term goal.

- Using the latest high-resolution climate model we have demonstrated that it is possible to produce much improved simulations of the North Atlantic Oscillation (NAO) and European winter climate on timescales of a few months ahead. This offers, for instance, the prospect of better seasonal forecasts to help manage the use of renewable energy over the long-term transition to a low-carbon economy.

Introduction

The scientific evidence for climate change and the contribution of human activity continues to strengthen through research undertaken worldwide, as demonstrated by the release in September 2013 of the latest report on climate science from the Intergovernmental Panel on Climate Change (IPCC). The Met Office Hadley Centre — a world-leader in climate research, modelling and projections — plays a key role in adding to the body of global knowledge on climate variability and change, including the IPCC's report.

Through a focused programme of research spanning 2012–2015 and funded by the UK Government, the Met Office Hadley Centre provides useful, up to date and impartial climate information to inform UK Government policy. This first-class science underpins decisions on mitigation, adaptation and energy requirements in response to future climate change.

As the three-year programme reaches its halfway point, important new insights are being made into our understanding of changes in the Earth's climate system, from the monitoring of climate change indicators through to potential impacts arising from these changes.

Observations

Observed global change

The accumulation of carbon dioxide (CO_2) in the atmosphere from human activities is unequivocal. In 2013, the atmospheric concentration of CO_2 — the most important anthropogenic greenhouse gas — briefly reached 400 parts per million (ppm) (see Figure 1, inset), unprecedented in 800,000 years. Most of the warming of the Earth's surface since the mid-20th century is very likely due to increases in CO_2 and other greenhouse gases.

Records of global near-surface temperature from three independent datasets show that the world has warmed by around 0.85 °C since 1880 (Figure 1). Much of this warming has occurred since the middle of the 20th century, with a rise of around 0.72 °C from 1951–2012. The global temperature for 2012 measured 0.45 ± 0.1 °C above the climatological average (1961–90). This ranks it as the ninth warmest (best estimate) since 1850 in the HadCRUT4 dataset produced jointly by Met Office Hadley Centre and University of East Anglia (UEA) Climatic Research Unit. The El Niño Southern Oscillation, which temporarily tips the Earth into warmer or cooler phases, became neutral in early 2012.

Many additional indicators or 'essential climate variables' are used to monitor the state of the climate system, revealing changes in global and regional climate. In addition to long-term average warming, the Earth has seen an increase in various climate extremes since the mid-20th century, such as the number of hot days. Since the early 1990s, global sea-level has risen at a rate of around 3 mm a year, mainly due to thermal expansion as the ocean heat content rises and through land-ice melt. 2012 was the 22nd consecutive year to show a negative annual glacial mass balance (i.e. loss of ice) as monitored by the World Glacier Monitoring Service.

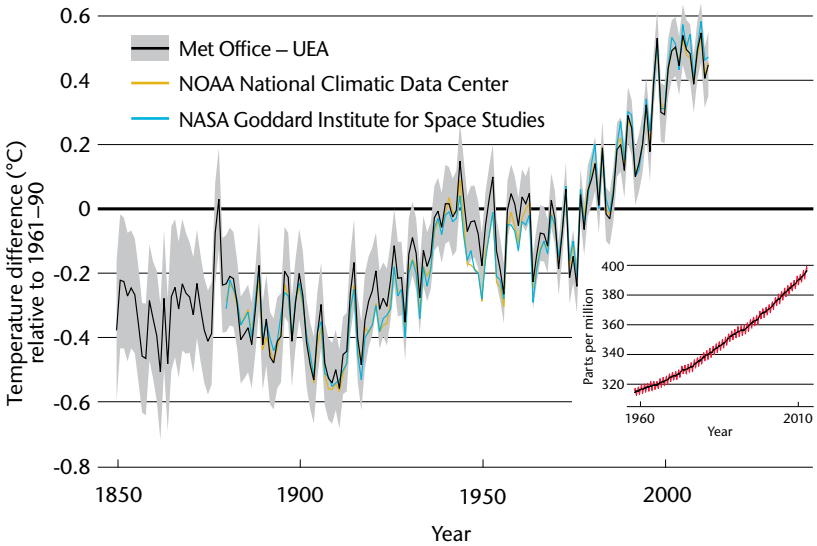


Figure 1: Observed annual global average near-surface temperatures (combined sea-surface and air temperatures over land) relative to 1961–90 for three datasets. Source: HadCRUT4; MLOST dataset, National Climatic Data Center at NOAA; Goddard Institute for Space Studies at NASA. Grey shading shows 95% confidence range for HadCRUT4. Inset shows the time evolution of atmospheric CO_2 concentrations measured at Mauna Loa Observatory, Hawaii.

The Earth's changing energy balance

While the most obvious indicator of global warming is the change in near-surface temperature, an alternative approach is to consider where the extra energy trapped by man-made greenhouse gases is stored. Evidence from the IPCC's Fifth Assessment Report suggests that more than 90% of the trapped energy will be stored in the ocean.

Over the last 10–15 years the rate of increase in the near-surface temperature has reduced compared to the rapid rise seen in preceding decades. Slowdowns in temperature rise have been observed in the past and are also seen in model simulations. However, the causes of past observed slowdown events are unlikely to always be the same.

The number of slowdowns that might be expected due to natural internal variations can be estimated using a long climate model experiment. For simulated warming rates of 0.15 °C and 0.1 °C per decade (the observed long-term rate of warming from 1951–2012 is around 0.12 °C), 15-year slowdowns would be expected around 3 and 4.5 times respectively per century. In these experiments a slowdown was defined as the warming trend dropping below 0.05 °C per decade. The model results also show that for a long-term warming rate of 0.1 °C per decade we might expect at least one slowdown event of 30 years to occur per century on average.

Consideration of the energy storage is helping to explain the most recent slowdown in surface warming. A component of the slowdown may be due to a reduction in the rate of increase of energy entering the Earth system. This is most likely to result from factors such as the number of small volcanic eruptions reflecting more sunlight back to space over the past few years as well as the expected and measured temporary reduction in the Sun's output. Changes in other factors such as man-made pollutant aerosols which also reflect sunlight cannot be completely ruled out.

However, observations of the ocean to a depth of 800 m (Figure 2) show a continued increase in heat content over the last 15 years and the evidence is mounting that some of the additional energy trapped in the system is heating the deep ocean below 800 m. This means that a significant component of the recent slowdown is also likely to be due to natural variations within the climate system. The natural variability appears to be associated with changes in the Pacific Ocean, and a natural feature of the climate system called the Pacific Decadal Oscillation seems especially important. Mechanistically, a greater fraction of the stored energy appears to be temporarily residing below the upper layers of the ocean; it is therefore isolated from the atmosphere and such a direct influence on surface temperatures.

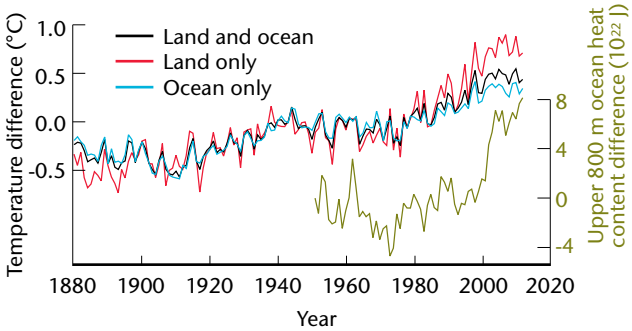


Figure 2: Black, red and blue lines show time series of global average surface-temperature (relative to 1961–90) for combined land-ocean, land only and ocean only (from Met Office – UEA). The green line shows heat content of the upper 800 m of the ocean relative to 1951–2006 (from Met Office analyses).

Causes of extreme events

Extreme weather events can cause catastrophic damage. Observations suggest that certain types of extremes are changing, and some of these changes can now be linked, in part, to human activity. The Met Office Hadley Centre played a key role in the Second Attribution Supplement to the annual 'State of the Climate' report published in the Bulletin of the American Meteorological Society which examined the causes of 12 extreme events occurring in late 2011 and 2012.

Drought, Iberia, Winter 2011/12	Record winter drought. Strongly influenced by the North Atlantic Oscillation (NAO) but human influence increased risk by around 25%.
Extreme rainfall, New Zealand, December 2011	Longer term man-made warming increased sub-tropical sea temperatures, enhancing atmospheric moisture content and rainfall. Likelihood of intense rainfall increased by 8–32%.
Cold snap, northern Europe, February 2012	Natural variability was found to have a large effect.
Low rainfall, East Africa, Spring 2012	Natural variability played a large part.
Low rainfall, central USA, Spring/ Summer 2012	Despite the accompanying heatwave, no clear evidence of human influence on the extreme low rainfall and extent and severity of the drought.
Heatwave, USA, Summer 2012	Warmest July on record. A very rare event estimated to have become four times more likely as a result of man-made climate change.

The green rows represent events where a human influence was detected.

Half of the studies found some evidence that human drivers of climate change were a contributing factor to the extreme events examined, though the effects of natural fluctuations of weather and climate on the evolution of all of the extreme events also played a role.

High rainfall, Europe, Summer 2012	The UK had its wettest summer since 1912. Some evidence for effect of warm North Atlantic sea-surface temperatures on rainfall. This is largely associated with natural variability, although Arctic sea-ice decline may have contributed.
Extreme rainfall, eastern Australia, end of Summer 2012	Largely associated with La Niña, with some evidence of longer term man-made warming of the sea surface having increased the risk of such high rainfall.
Extreme rainfall, Japan, July 2012	Effect of man-made warming was too small to be detected compared to natural variability of sea-surface temperatures.
Flooding, northern China, July 2012	Flood damage was large but rainfall amounts not unprecedented. Unable to confirm or reject influence of man-made climate change.
Sea-ice minimum extent, Arctic, September 2012	The record low minimum was a very rare event, outside the bounds of natural variability. A combination of long-term man-made warming and unusual meteorological conditions were found to be the main drivers.
Hurricane Sandy inundation, USA, October 2012	There is a substantial man-made contribution to sea level rise. This rise has led to increased risk of extreme water levels and inundation. A one in 435-year storm surge at Sandy Hook in 1950 is now a one in 295-year event, given similar meteorological conditions. Such a storm surge could occur once every 20 years by 2100 with continued greenhouse gas emissions.

The green rows represent events where a human influence was detected.

Carbon storage

The RCP2.6 greenhouse gas concentration pathway (described on facing page) offers a high chance of limiting warming to below 2 °C above pre-industrial levels. It is often interpreted as having a large and rapid development of biofuels combined with carbon capture and storage (CCS), alongside sizeable reductions in fossil fuel emissions. The combination of bio-energy and CCS (BECCS) allows the production of energy and the simultaneous removal of CO_2 from the atmosphere and could therefore be used to achieve negative carbon emissions (CO_2 removal). The amount implied is substantial — approximately 3 GtC (Gigatonnes of Carbon) removed per year by 2100 — compared with present day carbon emissions of around 9 GtC.

Using the Met Office Hadley Centre Earth System model, HadGEM2-ES, with a fully interactive carbon cycle, the impact of insufficient biofuels or viable CCS has been examined. Two additional emission scenarios were considered: one in which biofuels are developed but in which the emissions from biofuel combustions are not recovered through CCS (sensitivity study 1); and one in which biofuels are not employed and energy demands are met through additional fossil fuels without extra CCS (sensitivity study 2).

It was found in the RCP2.6 simulation that atmospheric CO_2 peaks around the middle of the century before declining to around 435 ppm in 2100. Without BECCS and with additional fossil fuels emissions instead, CO_2 rises throughout the century towards 530 ppm in 2100. This contributes an additional 0.35 °C of warming by 2100 (Figure 3).

As this is a first look using state of the art Earth system models, we have not yet included certain biophysical effects associated with changes in land use on, for example, surface reflectivity of sunlight. This will be addressed in future work.

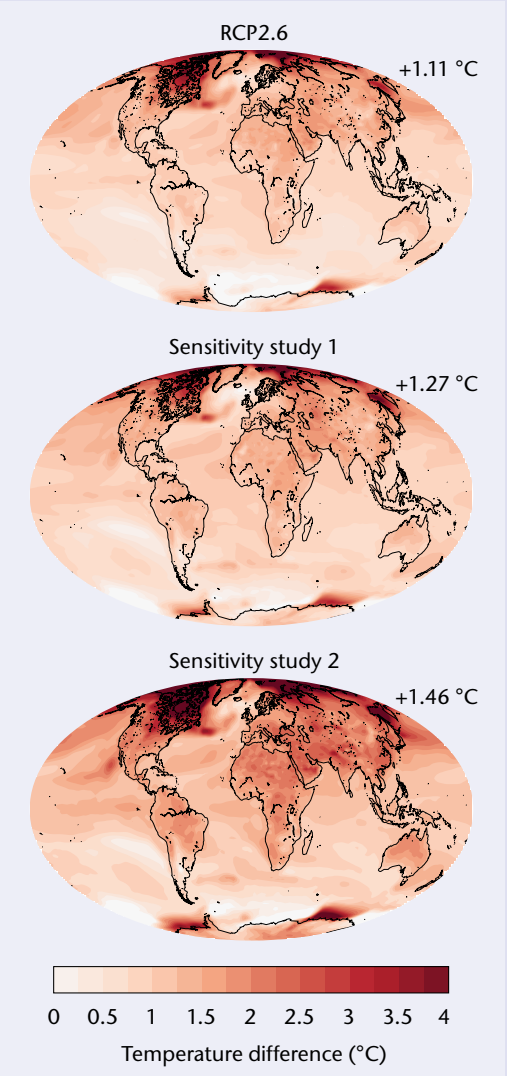


Figure 3: Change in global temperature over the 21st century (2080–2100 relative to 1986–2005) as simulated by HadGEM2-ES for RCP2.6 and scenarios of bio-energy carbon capture and storage.

The carbon budget

Total human driven emissions of greenhouse gases since the Industrial Revolution are approximately 550 GtC. Some two-thirds or more has come from the burning of fossil fuels and industrial activities, with the remainder from deforestation and other land use changes.

A key development in the IPCC Fifth Assessment Report is a linking of cumulative emissions to the global average near-surface warming. For a likely chance of staying below the UNFCCC global warming limit of no more than 2 °C above pre-industrial levels this equates to limiting total emissions of CO_2 to less than 1000 GtC, or around 800 GtC if the effects of other greenhouse gases are also taken into account. The atmospheric component of the carbon budget over time is shown in Figure 4.

Figure 5 shows the cumulative CO_2 emissions for RCP2.6 and the sensitivity experiments with either no BECCS or no biofuels included. The absence of biofuels takes the carbon emissions to a level where the temperature is more likely to exceed 2 °C relative to pre-industrial levels, consistent with Earth system model experiments.

The Representative Concentration Pathways (RCPs) are plausible future pathways of greenhouse gas and aerosol concentrations. RCP2.6 is an aggressive mitigation scenario where radiative forcing peaks at 3.1 Wm^{-2} (Watts per square metre) by mid-century, reducing to 2.6 Wm^{-2} (around 475 ppm of CO_2 equivalent) by 2100.

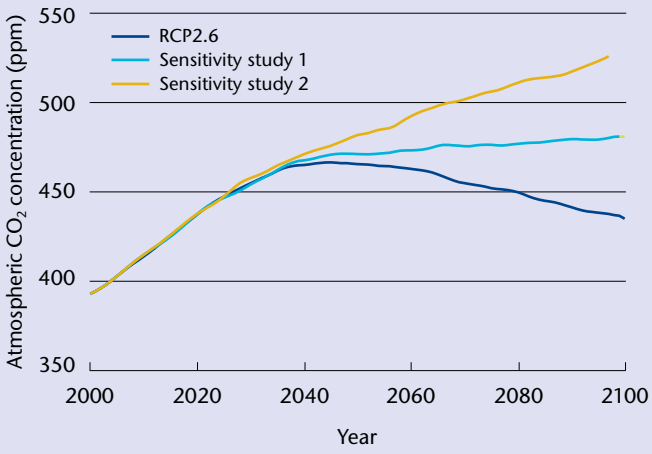


Figure 4: Future simulations of atmospheric CO_2 concentration in the HadGEM2-ES model including various scenarios of bio-energy carbon capture and storage.

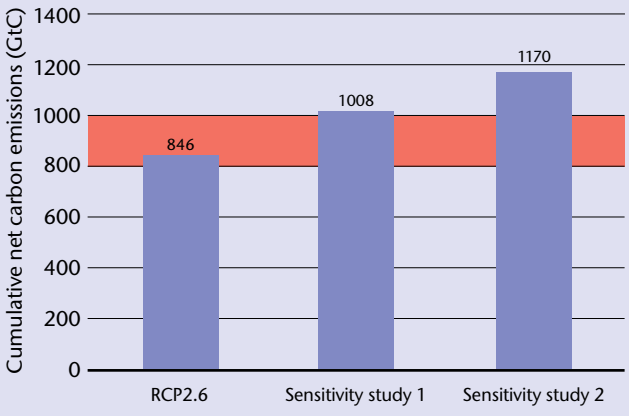
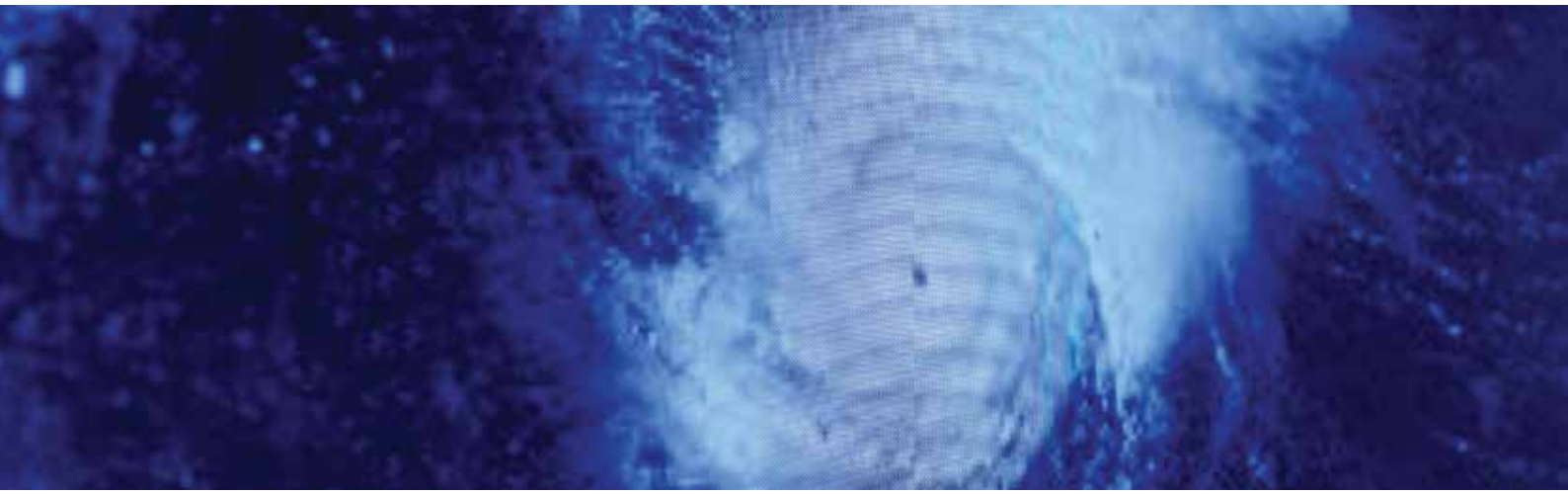


Figure 5: Cumulative net carbon emissions including negative emissions from pre-industrial to 2100 for RCP2.6 and its variants from HadGEM2-ES. Red band shows the carbon budget from the IPCC Fifth Assessment Report.

Aerosols: another man-made climate driver



Modulating the frequency of North Atlantic tropical storms

North Atlantic tropical storm activity varies substantially on decadal timescales and it had been thought that this variability was largely driven by natural changes in ocean circulation. However, new research suggests that man-made aerosol emissions may have had a primary influence on tropical storms in the 20th century, reducing their frequency and modulating their variations over time.

The Met Office Hadley Centre Earth System model, HadGEM2-ES, is able to reproduce much of the observed decadal variability in North Atlantic tropical storms (Figure 6), but only when the model includes changes in man-made aerosol emissions. Following clean air legislation in the 1970s and 80s, and a subsequent reduction in aerosols, the frequency of both observed and model-simulated tropical storms was found to increase. This work highlighted both the potential importance of anthropogenic aerosols and the remaining uncertainty regarding the interaction between aerosols and clouds in current climate models.

Aerosols are small particles suspended in the atmosphere which can be of natural origin (e.g. dust or sea-salt) or a by-product of industry or electricity generation. They have a direct effect upon the climate by reducing the amount of sunlight which reaches the Earth's surface and also an indirect effect on the climate by altering the brightness and lifetime of clouds. Research by the Met Office Hadley Centre shows that it is becoming more apparent that aerosols are affecting many aspects of regional climates in a number of important ways.

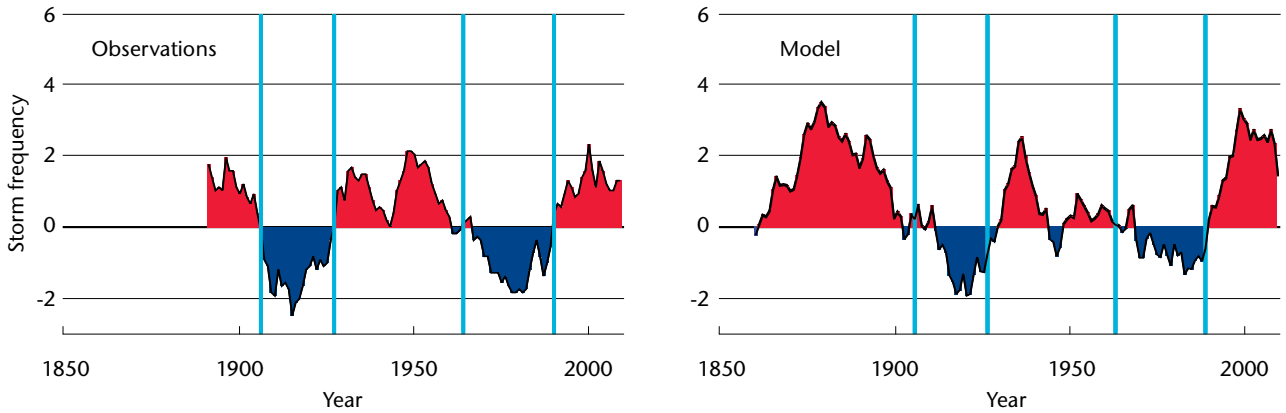


Figure 6: 11-year running mean of North Atlantic tropical storm frequency (relative to 20th century mean) from observations (left) and as modelled with a number of simulations of the Met Office Hadley Centre climate model HadGEM2-ES (right). The observed 20th century mean was six storms per year. Vertical lines show times of the transition between active/inactive periods of observed tropical storm activity.

Suppressing African rainfall

The Sahel drought between the 1970s and 90s led to 100,000–250,000 deaths, 10 million refugees and 30 million people in urgent need of food aid. Research shows clear observational evidence that past volcanic eruptions in the northern hemisphere contributed to significant drought in the Sahel, and that state of the art climate models are able to reproduce these observed droughts.

Observations from 1900–2010 show the four driest Sahelian summers were preceded by substantial volcanic eruptions in the northern hemisphere. HadGEM2-ES simulated two instances of the atmospheric effects of aerosols from volcanic eruptions — Katmai in 1912 and El Chichón in 1982 — demonstrating that climate models can capture the observed response and help to explain the mechanisms involved. The study suggests that seasonal Sahelian rainfall anomaly predictions following volcanic eruptions are also possible with HadGEM2-ES. These predictions may be beneficial for disaster relief efforts.

Delaying the intensification of the Earth's water cycle

Instrumental measurements of land precipitation since the early 20th century do not show such a clear increasing trend as might be expected in a warming world. The discrepancy cannot be explained without considering the effects of atmospheric aerosols.

By analysing a number of international climate models driven with both greenhouse gases and aerosols, a detectable weakening of the water cycle between the 1950s and 80s is revealed. Simulations with increasing greenhouse gases but no aerosol change show the expected increase in precipitation. Therefore, it appears that humans may be affecting rainfall through both the production of greenhouse gases and aerosols, with the aerosol effect holding back some of the expected increases (Figure 7). Future reductions in man-made aerosols could result in global precipitation increasing more rapidly than previously expected with consequences for mitigation and adaptation.

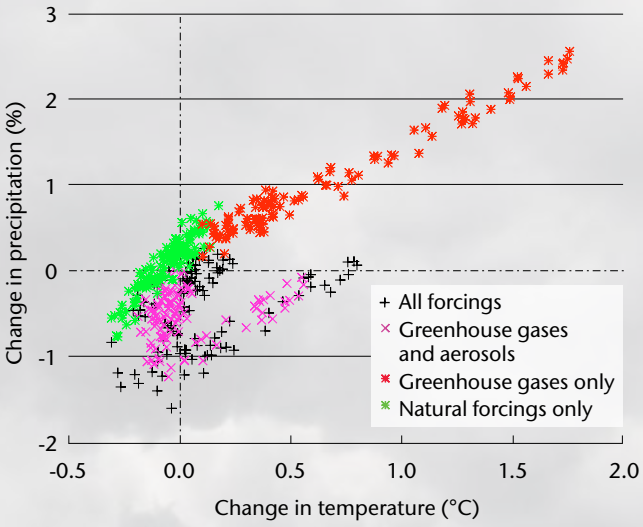
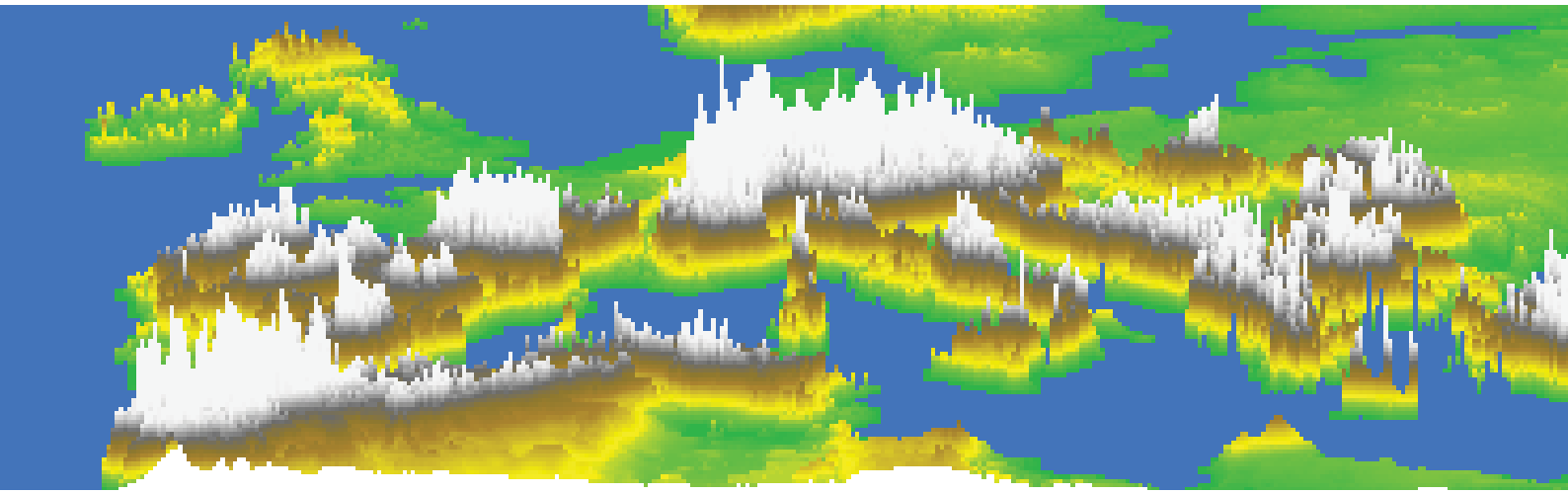


Figure 7: Change in global annual mean precipitation along with change in temperature for different climate forcings as simulated by the Met Office Hadley Centre model, HadGEM2-ES, for the period 1900–2005.

New developments in climate modelling



High-resolution climate modelling

The ability of climate models to simulate weather and climate processes and localised extreme events is essential to delivering information for resilience and adaptation planning. However, this is constrained by model resolution and computing power. Improvements in both of these have been shown to contribute to better representations of key phenomena.

In partnership with the University of Reading, advances in climate modelling have been made using higher spatial resolution computer models. These advances were made possible through increases in computing power. As part of the PRACE-UPSCALE[1] project, two versions of the Met Office climate model were configured to run at different global resolutions on a high-performance computing facility in Stuttgart, Germany.

The results showed that a minimum spatial scale of around 60 km is needed to capture the main processes that transport water from ocean to land (primarily via mid-latitude storms). At larger scale these modelled storms are too weak, leading to a deficit in horizontal transport of moisture and a false dominance of local evaporation and precipitation.

For many other processes, such as atmospheric convection, finer spatial scales are necessary. These finer scales, which require computationally intensive processing, are currently being investigated.

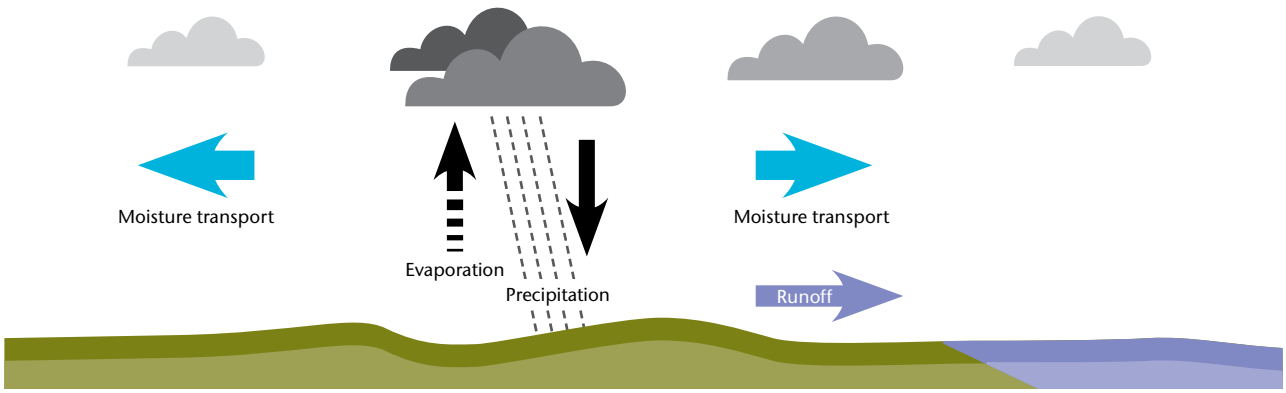


Figure 8: Schematic diagram of the water cycle.

[1] PRACE stands for Partnership for Advanced Computing in Europe (see www.prace-ri.eu). UPSCALE stands for 'UK on PRACE: Weather Resolving Simulations of Climate for Global Environmental Risk'.

Improved predictions of European winters

Advances in computer modelling have led to improvements in weather forecasts up to a few days ahead and in long-term projections of climate out to a few decades. There is a growing demand from planners and policymakers for accurate predictions of climate and associated weather on seasonal timescales. For example, advanced warning of severe winter conditions a month or more ahead could lead to action that reduces the risk of weather-related disruptions to society, provide climate predictions for the renewable energy industry, and serve as the early warning system as extreme events driven by climate change begin to unfold. Improved near-term prediction capability may be a key part of the decision-making process in the transition to a resilient low carbon economy.

Year to year fluctuations in European and North American winters are known to be dominated by a form of natural variability known as the North Atlantic Oscillation (NAO) but have exhibited relatively low levels of predictability in previous climate prediction systems. Slowly varying elements of the climate system, such as temperature in the Atlantic Gulf Stream, remote effects of El Niño and other precursors to the NAO, are now being better captured by models.

Using the Met Office Hadley Centre's latest high-resolution climate model, much improved predictions of the winter NAO have been achieved (Figure 9). These retrospective forecasts, initiated around 1 November each year, correlate well with surface temperature (Figure 10) in the following winter (December–February). This has been made possible through better understanding of the processes that drive winter climate and their representation in the climate model, notably through higher ocean resolution, a comprehensive representation of the stratosphere and interactive sea-ice physics.

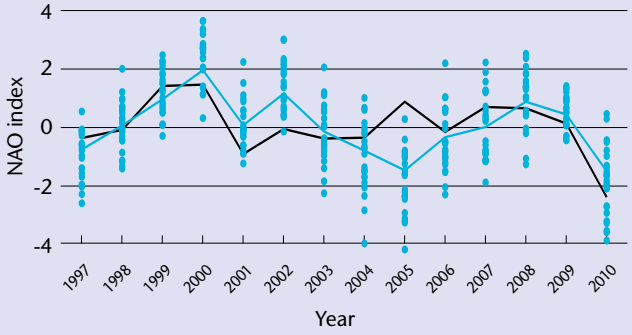


Figure 9: NAO index for December to February (normalised): observations (black line); mean value from multiple forecasts (blue line); and individual forecasts (blue dots) for lead times of one to four months.

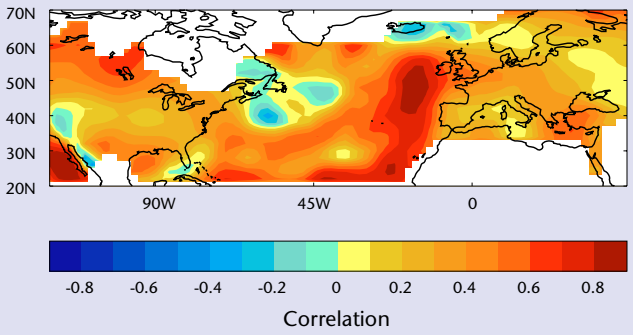


Figure 10: Relationship between mean model forecast NAO and winter mean temperature. Larger magnitudes indicate a stronger link between the NAO and local temperature.

Collaboration

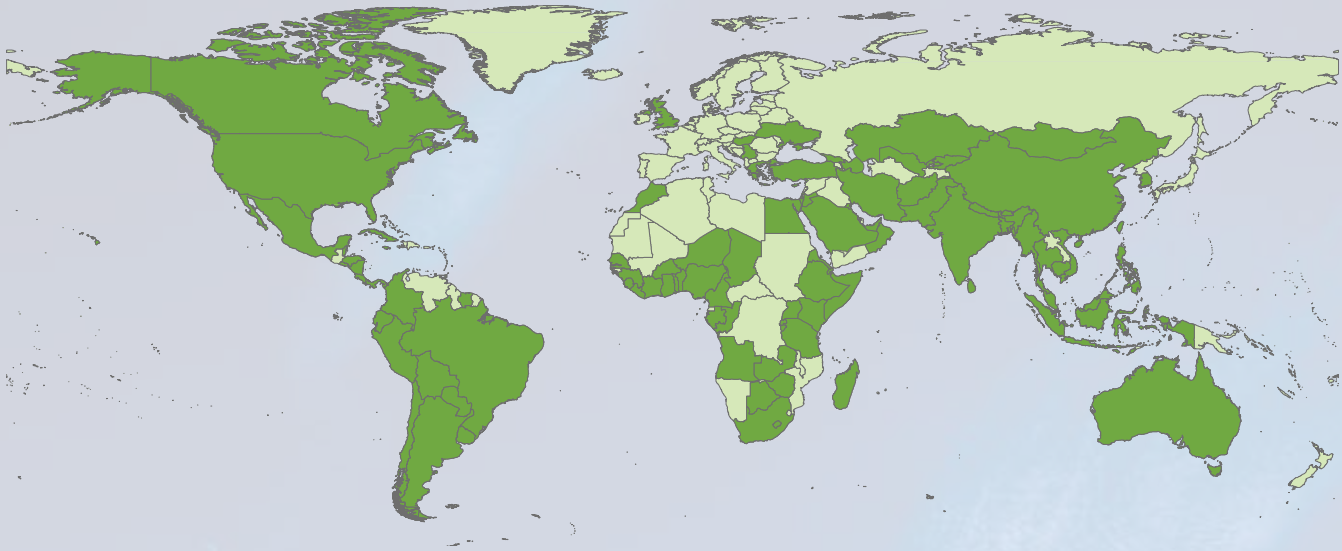


Figure 11: Over 100 countries across the world, indicated in dark green, are currently using PRECIS.

Collaboration and strong partnerships between the Met Office Hadley Centre and the wider UK and international scientific community are becoming increasingly important for ensuring the provision of robust and timely climate information to policymakers. Here, we summarise a small selection of collaborations with international partners.

Met Office Unified Model

Scientific collaboration with weather and climate centres around the world is helping to develop the capability of the Met Office's Unified Model (UM). The UM can simulate a range of timescales, from the next few hours for weather forecasting to more than a century ahead for climate change projections, and on local to global spatial scales. The UM is widely used by the UK academic community. In addition, users of the UM for climate and seasonal simulations include centres in Australia, India, New Zealand, Singapore and Republic of Korea. The information we receive back from users helps us to improve the model further.

Tools for regional climate modelling in developing countries

The PRECIS (Providing Regional Climates for Impacts Studies) system, developed by the Met Office Hadley Centre, forms the core of a capacity building and technology transfer programme enabling scientists in developing countries to produce spatially detailed information on climate change. PRECIS has been used extensively to inform different countries' communications to the UNFCCC and serves as a useful adaptation tool.

Climate Science Research Partnership

The Climate Science Research Partnership (CSRP) between the Met Office Hadley Centre and the UK Government's Department for International Development undertakes research into the drivers of variability and change in the African climate. The CSRP has entered its second phase with a focus on: assessing the reliability of new modelling systems for Africa; improving understanding and modelling of climate processes; climate change scenarios for 10–40 years ahead; and communication and knowledge sharing of climate information across Africa.

''The Met Office Hadley Centre is one of the world's foremost climate research centres with a reputation for the highest scientific excellence.

Its Climate Programme is invaluable in providing up to date scientific evidence to meet climate policy needs in the UK and abroad.

I greatly value its work and I am most pleased that the Met Office Hadley Centre has forged so many links to scientists throughout the world and produced scientific products that are so widely used.''

Rt Hon Edward Davey,
MP and Secretary of State for Energy and Climate Change

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